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14. ABSTRACT
Research is reported into the causes of various scattering enhancements from a variety of targets in water including cylindrical and spherical metallic shells, circular plates, solid cylinders, and plastic or rubber targets for various shapes. Some of the enhancements are relevant to interpreting sonar images. Quantitative ray theory was developed to predict the observed scattering amplitudes. Acoustic holography was used to confirm the modeled plate response. Measurement methods developed include: wide bandwidth acoustic sources, helicoidal acoustic wave sources, and magnetic methods for exciting torsional and flexural modes. Other research concerned the acoustics of suspended particles and caustics and related research on light scattering and bubbles.

15. SUBJECT TERMS
Acoustical Scattering, Ray Methods, Cylinders, Plastic Cylinders, Rubber Cylinders, Cylindrical Shells, Helical Rays, Acoustical Holography, Circular Plates, Cubes

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I. Introduction

Grant N00014-92-J-1600 was through the *ONR Physical Acoustics Program* (Code 331) for research described in a series of proposals starting with a proposal submitted in 1992. The titles and the detailed subject matter of each proposal varied, however there was a common theme of "Geometrical Aspects of Scattering and Physical Effects of Sound." Some of the graduate students supported by this grant had previously been supported by other ONR grants that had expired by the time their support was provided by this grant. This grant was augmented by two ONR-DOD AASERT awards to facilitate support of additional US citizen graduate students. One of those awards was assigned a separate grant number (N00014-97-1-0614) and the Final Report for that award was submitted in March 2001. For all of the students supported by AASERT awards, the principal budget for supplies and services was provided by the parent grant (N00014-92-J-1600). Graduate students whose research support was provided entirely or in part from this grant are listed in this report and in a separate list compiles the completed graduate (M. S. and Ph. D.) dissertations. Some of the Annual Technical Reports issued from this grant are archived at DTIC and the relevant information needed to access those reports is also listed.

Publications that were supported entirely or in part by this grant are listed. Some of the listed publications include research that was begun with support from earlier research grants. In most cases the primary means of disseminating the research results was through peer-reviewed journal publications. In some cases book chapter were published and these are listed separately. In many cases those chapters were also peer reviewed. Publications by other modes are also listed separately as are the conference presentations.

Only the topical areas of the research are listed in this report. The interested reader is encouraged to refer to publications, dissertations, and technical reports for details. Some of the research results involved following up new leads that became apparent during the course of the research. Figures 1 and 2 show some results noted in Section II (3) and (5).

In this report, references to publications are preceded by a letter that indicates the type of publication from the different sub-lists in Section IV. For example, peer-reviewed journal publications are preceded by an "A". Several publications are only briefly discussed in this summary, and for some research areas, the scope of the research can be seen best by inspecting the titles of the journal publications and the dissertations. *Items in Section IV (and graduate students listed in Section V) ending with * were only partially supported by grant N00014-92-J-1600 for the reasons explained above. This includes all publications involving collaborators not supported by this grant.*

References to research from earlier publications on other groups are indicated as [Rxx] and are listed in Section III.

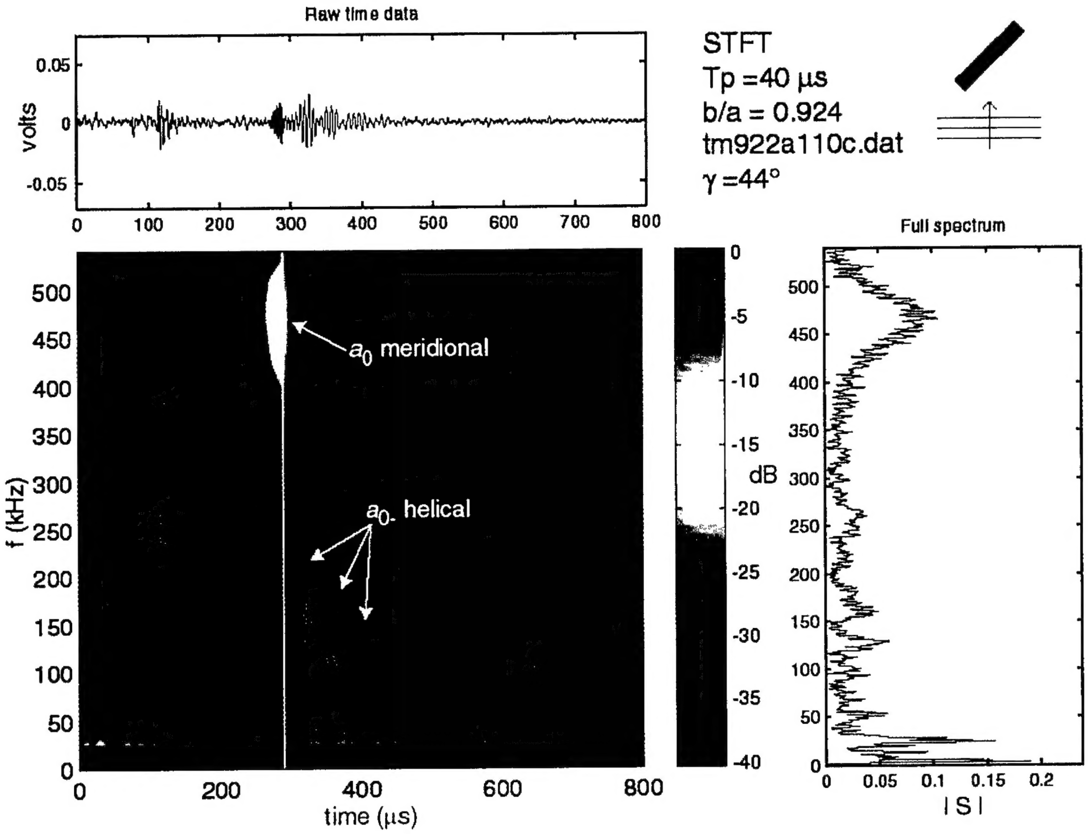
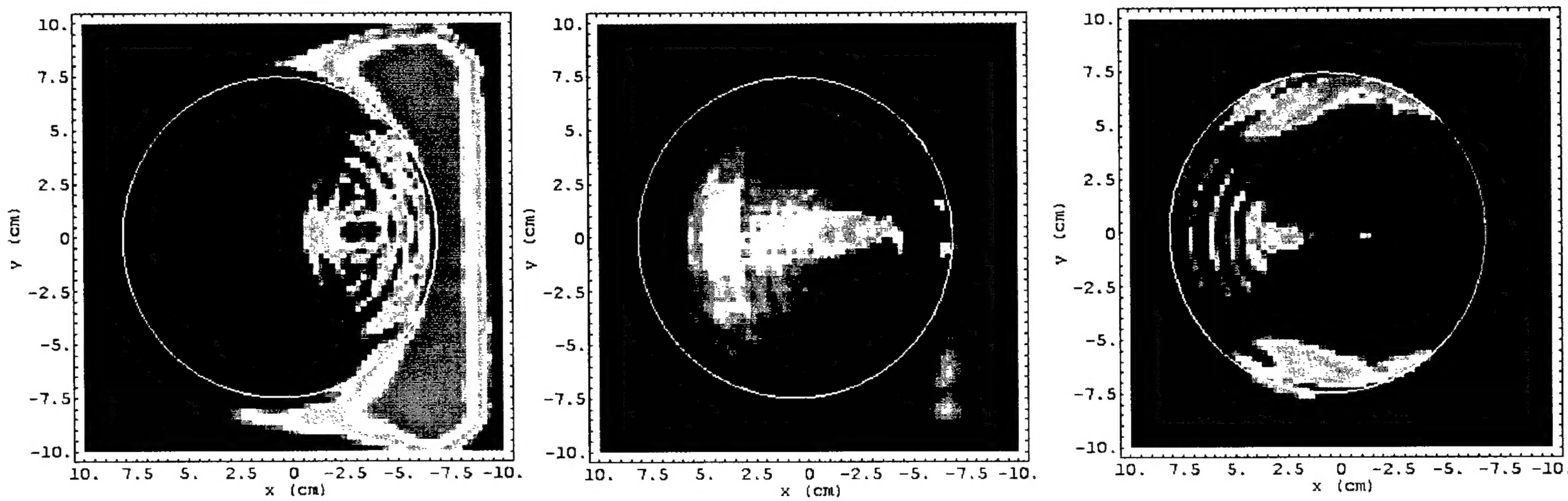


Fig. 1. This figure shows a time-frequency analysis of the measured response of a tilted steel cylindrical shell in water. Short time Fourier transforms (STFT) are used to display the spectral evolution of the backscattering as a function of time displayed on the horizontal axis. In this example, the shell is tilted at an angle gamma of 44 degrees relative to broadside illumination. Specific features of the evolving spectrum identified using ray theory include meridional and helical wave contributions to the backscattering by the bluntly truncated shell. The full spectrum and the STFT are normalized to the spectrum of the incident bipolar pulse. The spectral variation with tilt for this 7.6% thick shell was also studied [J. Acoust. Soc. Am. 103, 785-94 (1998)]. Ray theory was developed and tested for the amplitude of the large meridional contribution and the changes of the STFT with tilt were observed and explained. [From the 1998 Ph.D. thesis of S. F. Morse & J. Acoust. Soc. Am. 111, 1289-94 (2002).]



(a) (b) (c)

Fig. 2. Acoustic holograms of the response of a tilted circular plate in water demonstrating the importance of mode conversion to (and from) shear waves at the plate's edge. The white circle shows the border of the plate. The envelope of the out-of-plane velocity is shown at different times with the greatest velocity displayed as red. (a) (left) At the time of 42 μs the acoustic tone burst (incident from the left) has swept past most of the plate. The incident burst is visible as the red patch on the right. (b) (center) At 58 μs the leftward-propagating extensional-plate-wave direct-edge-reflection is visible in much of the central region of the plate. (c) (right) At 74 μs shear waves on the plate have mode-converted to leftward-propagating extensional waves visible near the top and bottom of the plate. Also the interference of counter-propagating extensional waves is visible in (c) along the horizontal diameter. The dynamical response of the plate enhances the amplitude of the acoustic backscattering. [From the 2000 Ph.D. thesis of B. T. Hefner. For a video display of this hologram see: Acoustics Research Letters Online 2(1), 55-60 (2001)]

II. Objectives and Summary of the Research

1. Quantitative Ray Methods for Scattering by Objects in Water

The objectives of this research were to overcome the limitations of prior ray formulations to enable the calculations of scattering amplitudes relevant to high-frequency sonar problems. The principal deficiencies in prior formulations that needed to be overcome included: (a) It is necessary to avoid limitations of some other formulations developed for use with thin shells at relatively low frequencies. This limitation is because formulations based on thin-shell or thin-plate mechanics fail to describe quantitatively (or in some cases qualitatively) the target dynamics at high frequencies. (b) It is necessary to allow for target shape, truncations, and classes of rays not previously considered. Some specific examples of results from this grant are outlined below. Initial results on high-frequency formulations pertaining to item (a) were published in [A1, A2, A5, A17, A18, A20-22, B2, D2]. Results pertaining to item (b) include [A12, A15, A23, A24, A28, A30, A32, A33, A36, A39, A40, A42-44, A46, A47, D5, D6, D8, D9].

2. Coincidence-Frequency, Backwards-Wave, and the Thickness "Quasiresonance" Scattering Enhancements (Kaduchak)

Initial research concerned extending the range of shell phenomena describable by prior formulations of Marston [R1] and Marston and Kargl [R2]. This stage culminated in Kaduchak's thesis [D2] which included experimental confirmation of the extension of ray theory to the coincidence-frequency enhancement of scattering by thin shells [A2, A5] and the high-frequency backwards-wave (negative-group velocity) enhancement [A14]. Some authors call this high frequency enhancement the "thickness quasi-resonance" [R3], though our ray theory, which was successful in describing the details of the enhancement, does not need to explicitly incorporate resonance properties. (The relevant shell properties are incorporated into the leaky wave phase velocity, group velocity, and damping [A14].) Our other numerical tests include [A1, A17, A20].

3. Analysis of Meridional and Helical Contributions for Tilted Cylinders (Gipson, Morse, Blonigen)

Meridional ray contributions for scattering by tilted cylinders involve a leaky wave that travels in the meridional plane on the cylinder. That plane is the one which contains the axis of the cylinder and the incident acoustic wavevector. The research was needed to explain in a quantitative way certain enhancements discovered by Kaduchak et al. [R4] in sonar images of truncated cylinders. An exact formulation for this scattering problem is not available. The ray analysis required the analytical approximation of certain diffraction integrals having a different form than previously considered [A23]. The result was extended to backscattering with variable tilt conditions by Gipson and Marston [A32]. Experimental and computational confirmation for various applications is given in the dissertations of Gipson [D5] and Morse [D6] and in [A23, A28, A32, A33, A40, A42, A43, A47, C9, C13]. See Figure 1. In related research, Blonigen [D9, A42, A46] analyzed and confirmed with computational models, high-frequency helical ray contributions of flexural waves above the coincidence frequency. It was necessary to allow for the interference of helical and meridional contributions. It was also necessary to include a weak wavevector anisotropy in the leaky wave parameters [D9, A42, A46].

4. Ray Theory and Experiments for Rayleigh Waves, Cubes, and Flat Ends of Tilted Cylinders (Gipson)

In addition to the aforementioned experiments on meridional and helical contributions from Rayleigh waves on a solid rod in water, Gipson [D5, A30, A36] studied backscattering enhancements due to Rayleigh waves on the flat surfaces of a cube and the flat ends of a circular cylinder. The ray theory applies Marston's formulations [A15, A24].

5. Holographic Imaging and Backscattering Enhancements in the Scattering by Tilted Elastic Disks (Hefner)

The problem of the backscattering of sound from circular disk-shaped objects has no exact solution but has potential applications to mine-counter measures. Hefner [D8] discovered several enhancements in the backscattering of sound by circular elastic disks. He succeeded in modeling some of the associated backscattering amplitudes with quantitative ray theory that extended the results in [A24, A36]. The relevant ray mechanisms were confirmed with acoustic holography at frequencies up to 300 kHz. The holograms display the elastic response of tilted plates to tone bursts. The time evolution may be viewed on ARLO publications [A39, A44]. Relevant mechanisms that produce long-lived responses involve mode conversions to in-plane shear waves (SH-waves) and to edge waves on the disk. See Figure 2. A small hydrophone was scanned near the plate and the wavefield was back-propagated to the plane of the plate [D8, R5].

6. Backscattering Enhancements for Plastic Targets in Water (Hefner, Blonigen)

For many plastics, the velocity of shear waves is less than the speed of sound in water. This makes it necessary to modify the ray analysis from the simpler case of a metallic or ceramic elastic target. Several new backscattering enhancements for plastic targets were proposed, demonstrated, and (in some cases) analyzed with quantitative ray theory. These include: (a) an enhancement in the backscattering by tilted plastic or rubber cylinders associated with a merging of caustics from certain internal rays [D9, A37]; (b) Rayleigh waves on plastics (which are subsonic relative to water) [D8, A38]; (c) enhancements specific to tilted plastic disks [D8]. In addition, Hefner studied computationally various enhancements of the scattering by plastic shells in water [D8]. The backscattering enhancement (a), studied by Blonigen, was also confirmed with analogous light scattering experiments [A45]. Ray theories constructed were useful for acoustical wave-number-radius products (ka) as small as 2 (for plastic spheres) and 8 (for tilted cylinders).

7. PVDF Sheet Source and Wide Band-Width Scattering (Kwiatkowski, Kaduchak, Morse)

To improve our capability of acquiring scattering data rapidly over an extremely wide range of frequencies, a new source and procedure for scattering experiments was developed. The source consists of a large PVDF sheet in direct contact with the water [A18, A28, A40, A43, D2, D6]. Our sources of this design were used to obtain scattering data for frequencies as high as 1 MHz [A40] and as low as 1 kHz [G49]. A typical range in tank experiments is 20 kHz - 400 kHz in which a pressure transient is radiated. This mode of operation is well suited for obtaining the time-domain transient response of

shells [A43]. See Figure 1. For obtaining wide bandwidth high frequency target spectra above 400 kHz, it can be advantageous to use a chirped excitation [A40, D6].

8. Low-frequency Target Detection Mechanisms (Hefner, Osterhoudt)

Hefner [A35, D8] demonstrated the magnetic excitation of low frequency shell modes including torsional modes. Osterhoudt [G90] began work which was successful in demonstrating the acoustic excitation of low-frequency organ-pipe modes of water-filled cylindrical shells as well as other modes having $ka << 1$. This was done in a 7000 gallon tank by using very small cylindrical shells.

9. Particle Suspensions: Acoustic Four-Wave Mixing and Novel Acoustic Signatures (Kwiatkowski)

Suspensions of particles are common in many ultrasonic applications including some in underwater acoustics. Graduate student support in this area was facilitated by AASERT augmentation. The emphasis was on the successful demonstration of a simpler co-linear geometry [D4, C12] for the non-linear process commonly known as four-wave mixing [A19, B4, C3]. A related detection method was characterized in which suspended particles detune a resonator after migrating in response to radiation pressure [A29]

10. Acoustical Caustics and Scattering by Rough Surfaces (Stroud, Dzikowicz)

Caustics caused by reflection of sound from curved surfaces are important for understanding fluctuations in target signatures for targets located near the top or bottom surfaces of the ocean. This grant assisted in supporting research on these problems, though the primary resources were from other sources [A8, A13, B2, C8, D3, G91]. The main objective was to describe complicated wavefields simply by applying the theory of diffraction catastrophes.

11. Other Research on Acoustic Radiation and Scattering (Matula, Stroud, Hefner)

Matula completed research (started with other ONR support) related to enhanced radiation mechanisms for subsonic waves on plates and membranes that cause acoustic evanescent wavefields [A3, A4, A16, D1]. Stroud published optical measurements of the transient dynamics of bubbles associated with rain noise [A7, C4]. Hefner succeeded in generating and characterizing acoustical helicoidal waves in water [A34, C14, D8]. The phase of a helicoidal wave advances linearly with angle around a propagation axis and the wave has an axial null. The helicoidal wave carries axial angular momentum and has unusual scattering properties [A34, G89]. Marston developed and carried out computational tests of a generalized optical theorem for objects having inversion symmetry in three-dimensions [A41] and two-dimensions [G85]. Marston and Thiessen succeeded in demonstrating that bubbles in insulating liquids subjected to oscillating electric fields have monopole oscillations which radiate sound [G42]. The method is potentially useful for investigating acoustic radiation by bubbles in simulated sediments.

12. Light Scattering Experiments Supportive of Acoustical Research (Kaduchak, Mount, Zhang)

When trying to understand and model complicated wavefields, it can be helpful to record the intensity patterns of the analogous optical wavefields. For this reason,

complicated diffraction catastrophes produced in light scattering were recorded and modeled [A2, A9, A10, A11, A27, A31, B1, B6]. An optical analogy of the acoustical caustic-merging transition [A37] was also investigated [A25, A26, A45, D7]. Some acoustical applications of the scattering of light by bubbles in water were documented [B5].

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IV. External Communications

Items ending with * had some partial support from another source as explained in Section I.

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B. Books or Chapters in Books

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3. P. L. Marston, "Introductory Chapter—Ultrasonics, Quantum Acoustics, and Physical Effects of Sound" (Invited Review Chapter) in *Encyclopedia of Acoustics*, M. J. Crocker ed. (John Wiley Press, New York, 1997) pp. 621-628.

4. H. J. Simpson and P. L. Marston, "Parametric Layers, Four-Wave Mixing, and Wavefront Reversal," accepted for publication in Nonlinear Acoustics, edited by M. F. Hamilton and D. T. Blackstock (Academic Press, 1998) pp. 399-420.*

5. P. L. Marston, "Light scattering by bubbles in liquids and applications to physical acoustics," in *Sonochemistry and Sonoluminescence*, L. A. Crum et al. eds. (Kluwer Academic Publishers, Netherlands, 1999) pp. 73-86. *(invited review)*

6. P. L. Marston, "Optical Caustics and Related Phenomena," in "On Minnaert's Shoulders: Twenty Years of Light and Color Conferences," C. L. Adler, Editor (Classic Reprints on CD-ROM Volume 1, Optical Society of America, 2000).

C. Conference Publications with Extended Abstracts

1. G. Kaduchak, P. L. Marston, and H. J. Simpson, "Observation of the E_6 diffraction catastrophe associated with the primary rainbow of oblate drops," in *Light and Color in the Open Air Technical Digest, 1993,* Vol. 13 (Optical Society of America, Washington, D.C., 1993) pp. 5-7.*

2. P. L. Marston and G. Kaduchak, "Secondary and higher-order generalized rainbows and unfolded glories of oblate drops: analysis and laboratory observations," in *Light and Color in the Open Air Technical Digest, 1993,* Vol. 13 (Optical Society of America, Washington, D.C., 1993) pp. 12-15.

3. H. J. Simpson and P. L. Marston, "Ultrasonic four-wave mixing mediated by a suspension," in *Advances in Nonlinear Acoustics*, Proceedings of the 13th International Symposium on Nonlinear Acoustics, edited by H. Hobaek (World Scientific, Singapore, 1993), pp. 644-649.*

4. J. S. Stroud and P. L. Marston, "Transient Bubble Oscillations Associated with the Underwater Noise of Rain Detected Optically and Some Properties of Light Scattered by Bubbles," in *Bubble Dynamics and Interface Phenomena,* J. R. Blake *et al.* (eds.) (Kluwer, Dordrecht, 1994) pp. 161-169.*

5. P. L. Marston, D. H. Hughes, G. Kaduchak, and T. J. Matula, "High-frequency radiation and scattering processes for shells and plates in water: Backwards waves, coincidence enhancements, and transition radiation," in *Third International Congress on Air- and Structure-Borne Sound and Vibration,* edited by M. J. Crocker (International Scientific Pub., Auburn AL., 1994) pp. 1573-1580.*

6. C. M. Mount and P. L. Marston, "Glare Points in the Refracted-Wave Scattering by Icicles and Other Tilted Dielectric Cylinders and the Caustic-Merging Transition," in *Light and Color in the Open Air,* Vol. 4, 1997 OSA Technical Digest Series, pp. 14-16.

7. D. S. Langley and P. L. Marston, "Generalized tertiary rainbow of slightly oblate drops: observations with laser illumination," in *Light and Color in the Open Air,* Vol. 4, 1997 OSA Technical Digest Series pp. 11-13.*

8. J. S. Stroud, P. L. Marston, and K. L. Williams, "Intensity moments of underwater sound scattered by a Gaussian spectrum corrugated surface: Measurements and comparison with a catastrophe theory approximation," in *High Frequency Acoustics in Shallow Water,* (edited N. G. Pace, E. Pouliquen, O. Bergem, and A. P. Lyons, Italy, 1997, SACLANTCEN Conference Series CP-45) pp. 525-532.*

9. P. L. Marston, "Approximation for leaky wave amplitudes in acoustic imaging: applications to high frequency sonar," presented at the 23rd International Symposium on Acoustical Imaging, Boston (1997).

10. P. L. Marston, S. F. Morse, and K. Gipson, "Resonances and other mechanisms for elastic contributions to the scattering of sound by objects in water," in Proceedings of the Resonance Meeting, Asilomar, CA (1997).

11. B. T. Hefner and P. L. Marston, "Magnetic excitation and acoustic detection of spherical shell modes in air and in water," in Proceedings of the Resonance Meeting, Asilomar, CA (1997).

12. C. S. Kwiatkowski "Acoustical resonator frequency shift due to the migration of suspended particles," in Proceedings of the Resonance Meeting, Asilomar, CA (1997).

13. S. F. Morse and P. L. Marston, "Meridional and helical ray contributions to backscattering by tilted cylindrical shells: High frequency tone burst and wide bandwidth measurements and interpretation," in Proceedings of the 16th International Congress on Acoustics (ASA, 1998) pp. 577-578.

14. P. L. Marston, K. Gipson, and S. F. Morse, "Convolution formulation for hgih-frequency leaky wave scattering enhancements for solids and shells with truncations: Evaluation of the surface integral and experimental and computational tests," in

Proceedings of the 16th International Congress on Acoustics (ASA, 1998) pp. 583-584.

15. B. T. Hefner and P. L. Marston, "Acoustical helicoidal waves and Laguerre-Gaussian beams: Applications to Scattering and to angular momentum transport," in Proceedings of the 16th International Congress on Acoustics (ASA, 1998) pp. 1921-1922.

16. P. L. Marston, "Catastrophe optics of spheroidal drops and generalized rainbows," *Conference on Light Scattering by Nonspherical Particles: Theory, Measurements, and Applications* (American Meteorological Society, 1998) pp. 13-15. *(invited review)*

17. P. L. Marston, S. F. Morse, and K. Gipson, "Leaky wave contributions to ultrasonic scattering amplitudes for truncated objects" Proceedings of the ASME, NCA**26**, 393-395 (1999).

18. P. L. Marston, F. J. Blonigen, B. T. Hefner, K. Gipson, S. F. Morse, "Comparison of radiation and scattering mechanisms for objects having Rayleigh wave velocities greater than or smaller than the speed of sound in the surrounding water," in Proceedings of the Resonance Meeting, Oxford, MS (1999).

19. B. T. Hefner and P, L. Marston, "Subsonic Rayleigh wave resonances on solid polymer spheres in water and backscattering enhancements associated with tunneling: experiments, models, and the relative significance of material and radiation damping," in Proceedings of the Resonance Meeting, Oxford, MS (1999).

20. P. L. Marston and B. T. Hefner, "Holographic identification of mechanisms for sonar backscattering enhancements: application to tilted elastic disks," Proceedings of the 17th International Congress on Acoustics (2001 on CD & to be published in paper).

21. P. L. Marston, F. J. Blonigen, K. Gipson, B. T. Hefner, and S. F. Morse, "Ultrasonic Backscattering Enhancements for Truncated Objects in Water: Quantitative Models and Tests and Special Cases," *IUTAM Proceedings on Diffraction and Scattering in Fluid Mechanics and Elasticity,* editors, I. D. Abrahams et al. (Kluwer Academic Publishers, accepted for publication).

D. Dissertations by Graduate Students

1. Thomas J. Matula, *Generation, Diffraction, and Radiation of Subsonic Flexural Waves on Membranes and Plates: Observations of Structural and Acoustical Wave Fields*, Ph.D. 1993.*

2. Gregory Kaduchak, *Mode Threshold and Transient Scattering Processes for High Frequency Scattering of Sound by Elastic Shells in Water*, Ph.D. 1994.*

3. John S. Stroud, *Twinkling of Underwater Sound Reflected by One Realization from a Gaussian Spectrum Population of Corrugated Surfaces*, Ph.D. 1995.*

4. Chris Kwiatkowski, *Ultrasonic Probes of Aqueous Particle Suspensions: Collinear Four-wave Mixing and Resonator Detuning*, Ph.D. 1997.

5. Karen Gipson, *Leaky Rayleigh Wave Ultrasonic Backscattering Enhancements: Experimental Tests of Theory for Tilted Solid Cylinders and Cubes*, Ph.D. 1998.

6. Scot F. Morse, *High Frequency Acoustic Backscattering Enhancements for Finite Cylindrical Shells in Water at Oblique Incidence*, Ph.D. 1998.

7. Catherine Mount, *The Evolution of the Airy Caustics and the Caustic Merging Transition for Light Scattered From a Tilted Dielectric Cylinders*, M.S. 1998.

8. Brian Todd Hefner, *Acoustic Backscattering Enhancements for Circular Elastic Plates and Acrylic Targets, the Application of Acoustic Holography to the Study of Scattering from Planar Elastic Objects, and Other Research on the Radiation of Sound*, Ph.D. 2000.

9. Florian J. Blongien, *Ultrasonic Backscattering Enhancements For Obliquely Tilted Cylinders In Water: Steel Shells And Plastic Cylinders*, Ph.D. 2001.

E. Technical Reports

1. P. L. Marston, Scattering and radiation of high frequency sound in water by elastic objects, particle suspensions, and curved surfaces, Annual Summary Report for N00014-92-J-1600, issued July 1994, DTIC Accession No. AD-A283093, 46 pages.

2. P. L. Marston, Scattering and radiation of high frequency sound in water by elastic objects, particle suspensions, and curved surfaces, Annual Summary Report for N00014-92-J-1600, issued June 1995, 35 pages.

3. P. L. Marston, Scattering and radiation of high frequency sound in water by elastic objects, particle suspensions, and curved surfaces, Annual Summary Report for N00014-92-J-1600, issued June 1996, DTIC Accession No. AD-A310720, 16 pages.

4. P. L. Marston, Geometrical Aspects of Scattering and Physical Effects of Sound, Annual Summary Report for N00014-92-J-1600, issued June 1997, 14 pages.

5. P. L. Marston, Geometrical Aspects of Scattering and Physical Effects of Sound, Annual Summary Report for N00014-92-J-1600, issued June 1998, 18 pages.

6. P. L. Marston, Final Technical Report "High Frequency Sonar Elastic Image Enhancements: Ray Theory, ONR-AASERT grant N00014-97-1-0614," issued April 2001, DTIC Accession No. AD-A389108, 9 pages.*

Note: For 1999, 2000, & 2001, the Annual Reports for grant N00014-92-J-1600 were submitted electronically to ONR.

F. Miscellaneous Publications

1. S. M. Bäumer, D. L. Kingsbury, and P. L. Marston, translators and editors of "Das elektromagnetische Feld um einen Zylinder und die Theorie des Regenbogens," by P. Debye, *Physikalische Zeitschrift,* Vol. 9(22), pp. 775-778 (1908) [Translation published in pp. 198-204 of *Selected Papers on Geometrical Aspects of Scattering* (SPIE Optical Engineering Press, Bellingham, WA, 1994)].*

G. General Conference Presentations

1. P. L. Marston and N. H. Sun, "Liquid-filled spherical reflectors: Analysis of glory ray amplitudes," J. Acoust. Soc. Am. **92**, 2472 (1992).*

2. P. L. Marston and N. H. Sun, "Liquid-filled spherical reflectors: the exceptional case of refractive index approaching two," J. Acoust. Soc. Am. **92**, 2472 (1992).*

3. G. Kaduchak and P. L. Marston, "E_6 diffraction catastrophe in light scattered near the rainbow region of an acoustically levitated spheroidal water drop," J. Acoust Soc. Am. **92**, 2474 (1992).*

4. P. L. Marston, "Classical sound waves as a coherent superposition of phonons," J. Acoust. Soc. Am. **93**, 2312 (1993).

5. H. J. Simpson and P. L. Marston, "Ultrasonic four-wave mixing mediated by a suspension of microspheres in water: Comparison between two scattering theories," J. Acoust. Soc. Am. **93**, 2384 (1993).*

6. P. L. Marston, "Fresnel width of the coupling regions of generalized leaky Lamb waves and Fermat's principle," J. Acoust. Soc. Am. **93**, 2411 (1993).

7. G. Kaduchak, P. L. Marston, and H. J. Simpson, "Observation of the E_6 diffraction catastrophe associated with the primary rainbow of oblate drops," at *Light and Color in the Open Air* (Optical Society of America, 1993) at Penn. State University.*

8. P. L. Marston and G. Kaduchak, "Secondary and higher-order generalized rainbows and unfolded glories of oblate drops: analysis and laboratory observations," at *Light and Color in the Open Air* (Optical Society of America, 1993) at Penn. State University.

9. S. S. Dodd, C. M. Loeffler, and P. L. Marston, "Retroreflective backscattering of sound in water due to Lamb waves on plates with corners: Observations," J. Acoust. Soc. Am. **94**, 1765 (1993).*

10. D. H. Hughes and P. L. Marston, "Time-frequency spectrograms of impulse scattering by shells: Quantitative comparisons with ray theory of Lamb wave contributions," J. Acoust. Soc. Am. **94**, 1823 (1993).*
11. C. S. Kwiatkowski, G. Kaduchak, and P. L. Marston, "Broadband impulse transducer for measurement of backscattering by objects in water," J. Acoust. Soc. Am. **94**, 1831 (1993).

12. P. L. Marston, "Convolution formulation of leaky wave contributions to scattering by plates and by cylinders and shells of variable curvature," J. Acoust. Soc. Am. **94**, 1861 (1993).

13. P. L. Marston, S. S. Dodd, and C. M. Loeffler, "Retroreflective backscattering of sound in water due to leaky waves on facets, plates, and corner truncations: Approximate theory," J. Acoust. Soc. Am. **94**, 1861 (1993).*

14. G. Kaduchak, T. J. Matula, and P. L. Marston, "Traveling wave decomposition of surface displacements on a cylindrical shell: Numerical evaluation displaying guided wave properties," J. Acoust. Soc. Am. **94**, 1861 (1993).

15. T. J. Matula and P. L. Marston, "Energy branching of a subsonic flexural wave on a plate at an air-water interface: Transition radiation and the acoustic wave field in water," J. Acoust. Soc. Am. **94**, 1877 (1993).*

16. G. Kaduchak, C. S. Kwiatkowski, and P. L. Marston, "Impulse response for backscattering by a thin spherical shell: Measurement and wave interpretation," J. Acoust. Soc. Am. **94**, 1877 (1993).

17. G. Kaduchak and P. L. Marston, "Observation of the prompt high-frequency enhancement of tone bursts backscattered by a thin spherical shell near the first longitudinal resonance," J. Acoust. Soc. Am. **94**, 1877 (1993).

18. K. L. Williams, J. S. Stroud, and P. L. Marston, "High-frequency forward scattering from Gaussian spectrum, pressure release, corrugated surfaces: Catastrophe theory modeling," J. Acoust. Soc. Am. **94**, 1890 (1993).*

19. J. S. Stroud, P. L. Marston, and K. L. Williams, "High-frequency forward scattering from Gaussian spectrum, pressure release, corrugated surfaces: Experiment and comparison with catastrophe theory," J. Acoust. Soc. Am. **94**, 1890 (1993).*

20. P. L. Marston, "Merging of launching or detachment points of weakly damped leaky waves on S-shaped surfaces and complex launching or detachment points," J. Acoust. Soc. Am. **95**, 2804 (1994).

21. P. L. Marston, "Enhancement of the total scattering cross section near the coincidence frequency of thin shells," J. Acoust. Soc. Am. **95**, 2804 (1994).

22. T. J. Matula and P. L. Marston, "Reflection of a subsonic flexural wave on a plate at an air-water interface and far-field observations of the transition radiation in water," J. Acoust. Soc. Am. **95**, 2972 (1994).*

23. P. L. Marston, "Symmetry and axial focusing in backscattering by elastic objects in water," J. Acoust. Soc. Am. **95**, 2999 (1994).

24. S. G. Kargl and P. L. Marston, "Coupling coefficient for leaky waves on thick spherical shells from elasticity theory," J. Acoust. Soc. Am. **95**, 3001 (1994).*

25. *Invited:* K. L. Williams, J. S. Stroud, and P. L. Marston, "High frequency acoustic (scalar field) forward scattering from Gaussian spectrum, pressure release, corrugated surfaces producing clusters of caustics: Catastrophe theory modeling and experimental comparisons," URSI (International Union of Radio Science) Meeting Program (Seattle, 1994) p. 308.*

26. P. L. Marston, G. Kaduchak, and H. J. Simpson, "Diffraction catastrophes, lips events, and the unfolding of glory scattering by dielectric spheroids: analysis and observations," URSI (International Union of Radio Science) Meeting Program (Seattle, 1994) p. 113.*

27. *Invited:* P. L. Marston, G. Kaduchak, and D. H. Hughes, "Backscattering enhancements and the impulse response of shells: Observations and ray theory," J. Acoust. Soc. Am. **96**, 3304 (1994).*

28. G. Kaduchak and P. L. Marston, "Impulse response of thin shells: source development, analysis of the bipolar specular contribution, and computations showing the effect of water on the inside of the shell," J. Acoust. Soc. Am. **96**, 3324 (1994).

29. K. Gipson and P. L. Marston, "Retroreflective backscattering of ultrasound due to Rayleigh waves on an elastic solid rectangular parallelepiped," J. Acoust. Soc. Am. **96**, 3325 (1994).

30. J. S. Stroud, P. L. Marston, and K. L. Williams, "High-frequency forward scattering from Gaussian spectrum, pressure release, corrugated surfaces: Measurements of twinkling exponents and the dependence of the second moment on distance from surface and pulse length," J. Acoust. Soc. Am. **96**, 3231 (1994).*

31. P. L. Marston and S. F. Morse, "Pressure impulse response measurements for elastic scatterers in water and regulation of the source spectrum," J. Acoust. Soc. Am. **97**, 3239 (1995).

32. P. L. Marston, "Variable phase coupling coefficient for leaky waves from resonance scattering theory and physical aspects of background contributions," J. Acoust. Soc. Am. **97**, 3283 (1995).

33. C. S. Kwiatkowski and P. L. Marston, "Collinear ultrasonic four-wave mixing mediated by a suspension," J. Acoust. Soc. Am. **97**, 3227 (1995).

34. *Invited.* P. L. Marston, "Time domain scattering of sound by elastic objects in water: leaky waves, backwards waves, and acoustic tunneling," presentation at 1995 PIERS (Progress in Electromagnetics Research Symposium) (Seattle, WA).

35. *Invited.* P. L. Marston, "Acoustical and Optical Levitation and Scattering: Fundamentals and Applications (abstract)," AAPT Announcer **25** (2), 68 (1995). [American Association of Physics Teachers Summer Meeting.]*

36. *Invited.* P. L. Marston, "Diffraction catastrophes and scattering by bubbles in water," presented at the Optical Society of America Annual Meeting (Portland, OR, September 1995).*

37. P. L. Marston and G. Kaduchak, "Transverse caustics produced in scattering by oblate drops of water: observations and analysis using wavefront principal curvatures," presented at the Optical Society of America Annual Meeting (Portland, OR, September 1995).

38. S. F. Morse, Z. W. Feng, and P. L. Marston, "High-frequency threshold processes for leaky waves on cylinders of variable thickness: fluid shell case," J. Acoust. Soc. Am. **98**, 2928 (1995).

39. J. S. Stroud, P. L. Marston, and K. L. Williams, "Intensity moments of underwater sound reflected by a Gaussian spectrum corrugated surface: Measurements and comparison with a catastrophe theory approximation (abstract)," J. Acoust. Soc. Am. **98**, 2912 (1995).*

40. C. S. Kwiatkowski and P. L. Marston, "Collinear ultrasonic four-wave mixing in suspensions of particles and bubbles (abstract)," J. Acoust. Soc. Am. **99**, 2560 (1995).

41. B. T. Hefner and P. L. Marston, "Electromagnetic excitation and acoustic spectroscopy of the quadrupole elastic mode of an empty nearly spherical shell (abstract)," J. Acoust. Soc. Am. **99**, 2594 (1996).

42. P. L. Marston, N. K. Hicks, and D. B. Thiessen, "Acoustic radiation from the monopole resonance of a bubble excited in a dielectrophoretic levitator by oscillating electric fields (abstract)," J. Acoust. Soc. Am. **99**, 2560 (1996).

43. S. F. Morse and P. L. Marston, "Backscattering due to ray reverberations between nonconcentric surfaces of a thick shell: Ray stability, transitions in wavefront shapes, and observed scattering enhancements due to focusing (abstract)," J. Acoust. Soc. Am. **99**, 2544 (1996). *For his presentation and essay, Morse received the "3rd*

Best Student Paper in Structural Acoustics and Vibrations," award for the yearly competition covering the 130th and 131st ASA meetings.

44. S. F. Morse, P. L. Marston, and G. Kaduchak, "High-frequency backscattering by thick finite cylindrical shells in water at oblique incidence: Experiments and calculations (abstract)," J. Acoust. Soc. Am. **99**, 2544-5 (1996).

45. P. L. Marston, "Spatial surface convolution approximation of three-dimensional leaky wave contributions to high frequency scattering," J. Acoust. Soc. Am. **100**, 2820 (1996).

46. P. L. Marston , "Light scattering and optical properties of bubbles in water relevant to studies of bubble population and dynamics," J. Acoust. Soc. Am. **100**, 2841 (1996).

47. S. F. Morse, P. L. Marston, and G. Kaduchak, "High-frequency backscattering enhancements for thick truncated cylindrical shells in water at oblique incidence," J. Acoust. Soc. Am. **101**, 3043 (1997).*

48. P. L. Marston, "Meridional leaky ray amplitudes for tilted cylinders and high frequency backscattering enhancements for finite cylinders," J. Acoust. Soc. Am. **101**, 3153 (1997).

49. S. F. Morse, B. T. Hefner, P. L. Marston, and K. L. Williams, "Wide bandwidth and low-frequency target response measurements with a large PVDF sheet source outside the laboratory," J. Acoust. Soc. Am. **101**, 3198 (1997).*

50. P. L. Marston, C. M. Mount, and D. B. Thiessen, "Bravais effective refractive index for tilted plastic cylinders and the caustic-merging transition in the meridional plane: Demonstration of an optical analogy," J. Acoust. Soc. Am. **102**, 3088 (1997).

51. F. J. Blonigen and P. L. Marston, "Backscattering enhancement for tilted plastic cylinders in water due to the caustic-merging transition: ultrasonic observations," J. Acoust. Soc. Am. **102**, 3088 (1997).

52. P. L. Marston and S. F. Morse, "Angle dependence of the meridional leaky-ray backscattering enhancement from the end of a tilted finite cylinder: Convolution analysis and a numerical test for shells," J. Acoust. Soc. Am. **102**, 3073 (1997).

53. K. Gipson and P. L. Marston, "Backscattering enhancements due to retroreflection of leaky Rayleigh waves at the truncation of a finite solid cylinder: Measurements and test of a theory," J. Acoust. Soc. Am. **102**, 3087 (1997).

54. B. T. Hefner and P. L. Marston, "Magnetic excitation and acoustic detection of torsional modes of spherical shells in water," J. Acoust. Soc. Am. **102**, 3131 (1997).

55. S. F. Morse, P. L. Marston, and G. Kaduchak, "Windowed displays of broadband impulse response measurements for finite cylindrical shells," J. Acoust. Soc. Am. **102**, 3131 (1997). *(First Place Award for 1997-1998 Structural Acoustics and Vibration Student Paper.)*

56. *Invited:* P. L. Marston, "Catastrophe optics of spheroidal drops and generalized rainbows," Conference on Light Scattering by Nonspherical Particles: Theory, Measurements, and Applications (American Meteorological Society, 1998) pp. 13-15.

57. S. F. Morse and P. L. Marston, "Meridional and helical ray contributions to backscattering by tilted cylindrical shells: High frequency tone burst and wide bandwidth measurements and interpretation," 16th International Congress on Acoustics, J. Acoust. Soc. **103**, 2813 (1998).

58. P. L. Marston, K. Gipson, and S. F. Morse, "Convolution formulation for high-frequency leaky wave scattering enhancements for solids and shells with truncations: Evaluation of the surface integral and experimental and computational tests," 16th International Congress on Acoustics, J. Acoust. Soc. **103**, 2814 (1998).

59. B. T. Hefner and P. L. Marston, "Acoustical helicoidal waves and Laguerre-Gaussian beams: Applications to Scattering and to angular momentum transport," 16th International Congress on Acoustics, J. Acoust. Soc. **103**, 2971 (1998).

60. B. T. Hefner and P. L. Marston, "Symmetric-wave coincidence-frequency and Rayleigh-wave tunneling backscattering enhancements for plastic shells and solid spheres in water," J. Acoust. Soc. Am. **104**, 1754 (1998).

61. K. Gipson and P. L. Marston, "Backscattering enhancement from leaky Rayleigh waves on the flat end of a tilted solid cylinder: Observations and Gaussian beam model," J. Acoust. Soc. Am. **104**, 1754 (1998).

62. S. F. Morse and P. L. Marston, "Meridional ray amplitudes for high-frequency backscattering from water-fluid tilted finite cylindrical shells," J. Acoust. Soc. Am. **104**, 1755 (1998).

63. P. L. Marston, B. T. Hefner, and F. J. Blonigen, "Backscattering enhancements for "plastic" scatterers in water and silt: Novel mechanisms and ray models for solids and shells," J. Acoust. Soc. Am. **104**, 1783 (1998).

64. *Invited:* P. L. Marston, C. S. Kwiatkowski, and H. J. Simpson, "Scattering enhancements and resonator frequency shifts resulting from the interaction between ultrasonic fields and suspended particles and bubbles," J. Acoust. Soc. Am. **105**, 1018 (1999).*

65. *Invited:* F. J. Blonigen and P. L. Marston, "Leaky wave scattering contributions of tilted thick cylindrical shells in water above the coincidence frequency: Ray theory and computational models, " J. Acoust. Soc. Am. **105**, 1224 (1999).

66. S. F. Morse, K. Gipson, G. Kaduchak, K. L. Williams, B. T. Hefner, and P. L. Marston, "Ultra-wide bandwidth backscattering measurements using a transparent flat PVDF sheet source," J. Acoust. Soc. Am. **105**, 1179 [EAA/ASA meeting, Berlin].*

67. F. J. Blonigen and P. L. Marston, "The caustic merging transition in the scattering of light by tilted dielectric cylinders and ultrasound by tilted plastic cylinders," APS Northwest Section meeting (1999).

68. P. L. Marston, F. J. Blonigen, B. T. Hefner, K. Gipson, S. F. Morse, "Comparison of radiation and scattering mechanisms for objects having Rayleigh wave velocities greater than or smaller than the speed of sound in the surrounding water," Resonance meeting, Oxford, MS (1999).

69. B. T. Hefner and P, L. Marston, "Subsonic Rayleigh wave resonances on solid polymer spheres in water and backscattering enhancements associated with tunneling: experiments, models, and the relative significance of material and radiation damping," Resonance meeting, Oxford, MS (1999).

70. B. T. Hefner and P. L. Marston, "Acoustical helicoidal wave transducers with applications for the alignment of ultrasonic and underwater systems," J. Acoust. Soc. Am. **106**, 2125 (1999).

71. P. L. Marston and F. J. Blonigen "Scattering enhancements for penetrable tilted circular cylinders in water: The computed evolution away from the meridional plane," J. Acoust. Soc. Am. **106**, 2158 (1999).

72. B. T. Hefner and P. L. Marston, "Backscattering enhancement mechanisms for thin tilted circular plates in water," J. Acoust. Soc. Am. **106**, 2159 (1999).

73. S. F. Morse and P. L. Marston, "Time-frequency analysis of the backscattering by tilted finite cylindrical shells," J. Acoust. Soc. Am. **106**, 2185 (1999).

74. P. L. Marston, S. F. Morse, and K. Gipson, "Leaky wave contributions to ultrasonic scattering amplitudes for truncated objects," Presented at the ASME IMECE (Nashville, 1999).

75. P. L. Marston, C. C. Barnes, Y. B. Zhang, and D. B. Thiessen, "Raman-Ray whispering gallery experiment and enhanced backscattering from merged caustics: Optical analogies of acoustical wavefields," J. Acoust. Soc. Am. **107**, 2847 (2000).*

76. F. J. Blonigen and P. L. Marston, "Backscattering enhancements of ultrasound by tilted solid plastic cylinders in water due to the caustic merging transition: High angular resolution scans," J. Acoust. Soc. Am. **107**, 2846 (2000).

78. B. T. Hefner and P. L. Marston, "Backscattering enhancements associated with mode conversion in thin tilted circular plates in water: Observations and Gaussian beam model, J. Acoust. Soc. Am. **107**, 2847 (2000).

79. B. T. Hefner and P. L. Marston, "Backscattering enhancements associated with antisymmetric Lamb waves on circular plates in water: Observations and imaging of the plate surface using acoustic holography," J. Acoust. Soc. Am. **108**, 2505 (2000).

80. F. J. Blonigen and P. L. Marston, "Backscattering by tilted cylindrical shells above the coincidence frequency caused by helical flexural waves," J. Acoust. Soc. Am. **108**, 2573 (2000).

81. P. L. Marston, "Generalized optical theorem for acoustic backscattering," J. Acoust. Soc. Am. **108**, 2640 (2000).

82. P. L. Marston, F. J. Blonigen, K. Gipson, B. T. Hefner, and S. F. Morse, "Ultrasonic Backscattering Enhancements for Truncated Objects in Water: Quantitative Models and Tests and Special Cases," presented at *IUTAM Symposium on Diffraction and Scattering in Fluid Mechanics and Elasticity*(2000). *Note: all IUTAM presentations ate by invitation.*

83. F. J. Blonigen and P. L. Marston, Backscattering from empty and water-filled tilted cylindrical shells due to leaky helical flexural waves: Comparison and ray theory. J. Acoust. Soc. Am. **109**, 2299 (2001).

84. P. L. Marston and B. T. Hefner "Acoustic backscattering and coupling processes for elastic and plastic circular disks in water: Direct and holographic observations," J. Acoust. Soc. Am. **109**, 2489 (2001).

85. P. L. Marston, "Generalized optical theorem for two-dimensional scattering: Applications to backscattering and arbitrary scattering angles," J. Acoust. Soc. Am. **109**, 2496 (2001).

86. *Invited:* P. L. Marston and B. T. Hefner, "Holographic identification of mechanisms for sonar backscattering enhancements: application to tilted elastic disks," 17th International Congress on Acoustics (Rome 2001).

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V. Graduate Students Supported that Completed a Degree (and Present Affiliation)

Students ending with * had received some partial support from another source as explained in Section I.

1. Thomas J. Matula, Ph.D. 1993 (Applied Physics Laboratory, University of Washington).*

2. Gregory Kaduchak, Ph.D. 1994 (Los Alamos National Laboratory).*

3. John S. Stroud, Ph.D. 1995 (Naval Surface Warfare Center, Coastal Systems Station).*

4. Chris Kwiatkowski, Ph.D. 1997 (Los Alamos National Laboratory).

5. Karen Gipson, Ph.D. 1998 (Grand Valley State University).

6. Scot F. Morse, Ph.D. 1998 (Western Oregon University).

7. Catherine Mount, M.S. 1998 (N/A).

8. Brian Todd Hefner, Ph.D. 2000 (Applied Physics Laboratory, University of Washington).

9. Florian J. Blongien, Ph.D. 2001 (Washington State University).

Current students who have not yet completed degrees: B. Dzikowicz* & C. F. Osterhoudt.

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